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Feasibility of Terrestrial laser scanning for collecting stem volume information from single trees

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ABSTRACT

Interest in measuring forest biomass and carbon stock has increased as a result of the United Nations Framework Convention on Climate Change, and sustainable planning of forest resources is therefore essential. Biomass and carbon stock estimates are based on the large area estimates of growing stock volume provided by national forest inventories (NFIs). The estimates for growing stock volume based on the NFIs depend on stem volume estimates of individual trees. Data collection for formulating stem volume and biomass models is challenging, because the amount of data required is considerable, and the fact that the detailed destructive measurements required to provide these data are laborious. Due to natural diversity, sample size for developing allometric models should be rather large. Terrestrial laser scanning (TLS) has proved to be an efficient tool for collecting information on tree stems. Therefore, we investigated how TLS data for deriving stem volume information from single trees should be collected. The broader context of the study was to determine the feasibility of replacing destructive and laborious field measurements, which have been needed for development of empirical stem volume models, with TLS. The aim of the study was to investigate the effect of the TLS data captured at various distance (i.e. corresponding 25%, 50%, 75% and 100% of tree height) on the accuracy of the stem volume derived. In addition, we examined how multiple TLS point cloud data acquired at various distances improved the results. Analysis was carried out with two ways when multiple point clouds were used: individual tree attributes were derived from separate point clouds and the volume was estimated based on these separate values (multiple-scan A), and point clouds were georeferenced as a combined point cloud from which the stem volume was estimated (multiple-scan B). This permitted us to deal with the practical aspects of TLS data collection and data processing for development of stem volume equations in boreal forests. The results indicated that a scanning distance of approximately 25% of tree height would be optimal for stem volume estimation with TLS if a single scan was utilized in boreal forest conditions studied here and scanning resolution employed. Larger distances increased the uncertainty, especially when the scanning distance was greater than approximately 50% of tree height, because the number of successfully measured diameters from the TLS point cloud was not sufficient for estimating the stem volume. When two TLS point clouds were utilized, the accuracy of stem volume estimates was improved: RMSE decreased from 12.4% to 6.8%. When two point clouds were processed separately (i.e. tree attributes were derived from separate point clouds and then combined) more accurate results were obtained; smaller RMSE and relative error were achieved compared to processing point clouds together (i.e. tree attributes were derived from a combined point cloud). TLS data collection and processing for the optimal setup in this study required only one sixth of time that was necessary to obtain the field reference. These results helped

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to further our knowledge on TLS in estimating stem volume in boreal forests studied here and brought us one step closer in providing best practices how a phase-shift TLS can be utilized in collecting data when developing stem volume models.

1. Introduction

Stem volume information is needed for sustainable planning of forest resources (Vanclay, 1994; Kangas and Maltamo, 2006; Bettinger et al., 2009; Pretzsch, 2009). It is highly correlated with biomass and bounded forest carbon (e.g. Pretzsch, 2009; Yu et al., 2013), which makes it an important attribute to monitor in understanding the effects of climate change (Penman et al., 2003). Assessment of national forest biomass and carbon stock is, in general, based on information on forest resources, i.e. estimates of the forested area and volume of the growing stock as reported by national forest inventories (NFIs) (Liski and Kauppi, 2000). The basis of these estimates is on estimating the stem volume of individual trees. The volume estimates reported are multiplied with simple biomass expansion and/or conversion factors to obtain biomass and carbon estimates (Penman et al., 2003). Stem volume can be converted into dry weight with wood density factor and furthermore total biomass with a biomass expansion factor, but these can be combined in one value (e.g. Penman et al., 2003; Lehtonen et al., 2004; FAO, 2006). Biomass and volume equations exist to some extent (Eamus et al., 2000; Keith et al., 2000; Jenkins et al., 2003; Zianis et al., 2005) and they can directly be applied to tree level biomass estimates.

Large area inventories on forest resources such as NFIs are based on plot-level field measurements that come down to measuring individual trees, i.e. measuring easy attributes (e.g. diameter-at-breast height, 1.3 m, dbh) and modelling the attributes of interest (e.g. stem volume and/or biomass). Traditional field measurement techniques are time consuming especially if destructive measurements only are required. Therefore, for developing models for stem volume or biomass for an individual tree, flexible and effectual field measurement techniques are required.

Terrestrial laser scanning (TLS) provides three dimensional (3D) data that can be used in measuring a tree stem. However, additional models and/or assumptions are required to obtain the full 3D reconstruction of the stem from TLS data. TLS has been widely studied related to forest inventory with various focus (Liang et al., 2016). TLS has been employed in estimating stem volume (Thies et al., 2004; Moskal and Zheng (2012); Pueschel et al., 2013; Astrup et al., 2014) and biomass (Holopainen et al., 2011; Yu et al., 2013) but also measuring stem form (i.e. diameters along the stem or stem curve) (see Pfeifer and Winterhalder, 2004; Henning and Radtke, 2006; Maas et al., 2008; Liang et al., 2014) of individual trees. TLS has thus proved to have potential for inventorying single-tree level attributes. The relative root-mean-square error (RMSE) of TLS-based dbh estimates has varied between 5.8% and 13.1% (Tansey et al., 2009; Lindberg et al., 2012; Kankare et al., 2014, 2015). However, measuring diameters to the tip of a tree can be challenging (Watt and Donoghue, 2005; Hackenberg et al., 2015; Xia et al., 2015). Thies et al. (2004) reconstructed 30% of the stem of a European beech and 22% of the stem of a Wild cherry automatically. In Liang et al. (2014), the highest diameters measured automatically, was possible to a relative height of 68.5% for Scots pine (*Pinus sylvestris* L.) and 61.0% for Norway spruce (*Picea abies* (L.) H. Karst.). However, e.g. Raumonen et al. (2013) were able to reconstruct the entire stem profile of one Scots pine using a 3D structural model. In addition, the tree height has been reported as an underestimate, varying from 0.64 m to 2 m (Hopkinson et al., 2004; Maas et al., 2008; Kankare et al., 2014), although differing results have been obtained. Liang and Hyyppä (2013) reported a mean overestimate of 1.3 m, and Calders et al. (2015) attained a RMSE of 0.55 m for TLS-based tree height when compared with destructively measured height. Tansey et al. (2009) were completely unable to measure the tree height, due to occlusion. Furthermore, wind conditions can affect the reliability of determining diameter and canopy size due to swaying of trees during scanning (Vaaja et al., 2016).

Forest conditions play a major role in collecting TLS data (see Kankare et al., 2015) ensuring that individual tree characteristics are visible and distinguishable to the scanner. TLS has widely been studied in forestry, related to detecting tree species (Othmani et al., 2013), estimating leaf area (Béland et al., 2014), and modelling small trees (Bienert et al., 2014; Hess et al., 2015). In addition to stem volume and profile, extensive research on stem and crown modelling in geometrical manner exist (Xu et al., 2007; Côté et al., 2011; Côté et al., 2012; Dassot et al., 2012; Eysn et al., 2013; Raumonen et al., 2013; Aiteanu and Klein, 2014; Delagrange et al., 2014; Hackenberg et al., 2014; Calders et al., 2015; Hackenberg et al., 2015; Raumonen et al., 2015). TLS data acquisition depends on the question addressed and best practices, i.e. a standard way of collecting and processing TLS data, for utilizing TLS operationally in various forested areas would be beneficial. The context of this paper is in developing stem volume equations at individual tree level with TLS data, but other TLS-based forestry applications have also been studied (Liang et al., 2016) and TLS has the potential to automatize and expand field measurements for forest inventory (Newnham et al., 2015).

Martins Neto et al. (2013) used four TLS scanning distances (5 m, 10 m, 15 m, and 20 m) for measuring diameters from sample trees, and concluded that the optimal scanning distance is related to tree height. Delagrange and Rochon (2011) also used several scan locations, but all of them were at same distance, i.e. 12 m, because their main interest was to estimate crown volume. Henning and Radtke (2006), on the other hand, had nine sample trees that were scanned at various positions at distances between 2 m and 7 m, but their emphasis was in registration of multiple point clouds without artificial reference targets. Dassot et al. (2012) and Schilling (2014) used TLS for volume estimates and scanned their sample trees from several locations and combined the point clouds (i.e. multiple-scan method) to obtained better results. They did not, however, take a stand on the optimal scan location or distance. To our best knowledge there are no studies related to establishing on optimal scan distance for estimating stem volume of an individual tree with TLS. In addition, the above-mentioned studies have all combined data sets from several scan locations into one point cloud, but we wanted to test whether it improves the results if the point clouds are processed separately (to minimize the effect of swaying caused by the wind).

A growing interest in utilizing TLS data as basis for developing stem volume equations exist. There are, however, many questions related to data acquisition and processing and should be answered before TLS can be utilized for this task. This study is our first investigation towards our goal of TLS-based stem volume equations; therefore the aim of this paper is to provide insight how TLS data should be acquired with the scanner used to provide accurate stem volumes for stem volume model development in boreal forest conditions studied here. The stem volume was considered as the recoverable volume, i.e. the volume was calculated as the stem volume above the highest root collar and with bark. The detailed reference permitted us to assess whether the TLS-derived stem volume was as accurate as the volume obtained with the destructive measurements. In addition, we took single scans from varying distances to investigate the effect of scanning distance on the volume estimates, and we selected the optimal scan locations to consider the effect of combining two point clouds from varying distances on stem volume estimates. In this study we tested whether more accurate stem volume estimates were obtained with multiple TLS scans and how the phase-shift scanner used in this study should be placed. This was done to enable us to deal with the best practices for TLS data collection (e.g. a single scan or multiple scans at a certain scanning distance) and to derive the stem volume from the point cloud in such a way that the stem volume estimate would still be adequate for further development of the stem volume equations.

2. Materials and methods

2.1. Reference measurements

The study area is located in Evo, southern Finland, which is part of the Boreal Forest Zone dominated by Scots pine, Norway spruce and birch (*Betula* L. sp.). The area in Evo is mainly managed forests, but includes recreational and protection areas. The study area included two sample plots, one from a *Vaccinium*- type forest (i.e. sub-xeric heath forest) (plot ID 1) and the other from a *Myrtillus*-type forest (i.e. mesic heath forest) (plot ID 2). The forest inventory attributes for the two sample plots are presented in Table 1.

The data consisted of nine trees, three from each main tree species in Finland, i.e. Scots pine, Norway spruce and birch, and the data collection was conducted in leaf-off conditions in early December 2015. The sample trees were selected in such a way that the dbh ranged approximately between 10 cm and 35 cm for each of the three tree species. The selection of the sample was based on the following thresholds defining the developmental classes: for *Myrtillus*-type forests the minimum of mean dbh for regeneration-ready forests is 26 cm for pine and spruce, and 27 cm for birch; for young forests the mean dbh varies between 8 cm and 16 cm; the limits for the mean dbh lies between these two classes for mature forests. Age was determined from the stump for the conifers samples. Two diameters from perpendicular directions were measured with steel calipers at 1.3 m above the highest root collar and the dbh of a sample tree was determined as an average of these two measurements. Tree height was determined with a Vertex clinometer (Haglöf Sweden AB, Långsele, Sweden), which estimates tree height based on distance and angle. Further detailed information on the sample trees is presented in Table 2.

After selecting the trees and measuring the dbh and height for the standing trees, the sample trees were cut down as close to the root collar as possible and pruned. The measurements from the harvested trees were incorporated in defining the reference stem volume for the TLS-based stem volume. The tree height of the harvested trees was measured with a measuring tape to an accuracy of 1 dm. Perpendicular diameters in two direction were measured with steel calipes to an accuracy of 1 mm at the root collar, at heights of 5 cm and 10 cm above the root collar, and then at every 10 cm to the top of the tree. If the measurement locations were to be over a branch knot, the diameter was measured from the upper side of the knot, which follows the practices used in measuring calibration data for harvesters in Finland. However, there were situations in which branch knots or pruned branch spots were so large (especially with birches) that it was not possible to obtain logical diameters from either side of the stem. In such cases, the diameters were then interpolated, based on the successfully measured diameter records above and below the particular spot before the analysis.

Although the stem diameters were measured at an accuracy of 1 mm, there was unevenness in the measurements, especially for birches (Figs. 1 and A.1), due to the branch knots and bark roughness. Therefore, a smoothing cubic spline curve was fitted to the measured stem diameters to level the unevenness of the measurements and estimate the stem volume. The parameter value for smoothing varied between 0.1 and 1.0 determining the amount of flattening of the cubic spline, i.e. 0.1 converges the smoothing spline near an interpolating spline following each diameter-height point whereas 1.0 flattens the spline closer to a linear least square estimate. The effect of the parameter value on the smoothing and then on the volume estimate was evaluated, based on the curve's ability to describe the butt and top parts of the stem, but also with the standard deviation of the stem volume estimates with the various smoothing parameters. Stem diameters at every 0.1 m starting at a height of 0.05 m were extracted from the fitted smoothed cubic splines, and the volume of each stem section was then estimated according to Huber's formula and the total stem volume was then estimated as the sum over all sections:

Table 1
Forest inventory attributes of the two sample plots. Dg is the mean diameter and Hg the mean height weighted by the basal area, BA is the basal area per hectare, Vol the stem volume per hectare and N/ha the number of stems per hectare.

Plot ID	Dg (cm)	Hg (m)	BA (m^2/ha)	Vol (m^3/ha)	N/ha
1	19.4	16.1	20.6	161.1	1016
2	23.0	21.9	24.4	259.1	664

Table 2
Details for the sample trees. dbh = diameter-at-breast height.

Tree ID	Species	Plot ID	dbh (cm)	Height (m)	Age	Size class
1	Pine	1081	18.9	17.0	38	Mature
2	Pine	1081	11.5	12.2	36	Young
3	Spruce	1086	26.7	22.6	69	Regeneration-ready
4	Birch	1086	28.2	26.9		Regeneration-ready
5	Birch	1086	13.9	21.3		Young
6	Birch	1086	19.1	21.9		Mature
7	Spruce	1086	14.3	14.9	61	Young
8	Pine	1086	30.0	23.9	55	Regeneration-ready
9	Spruce	1086	21.7	20.7	63	Mature

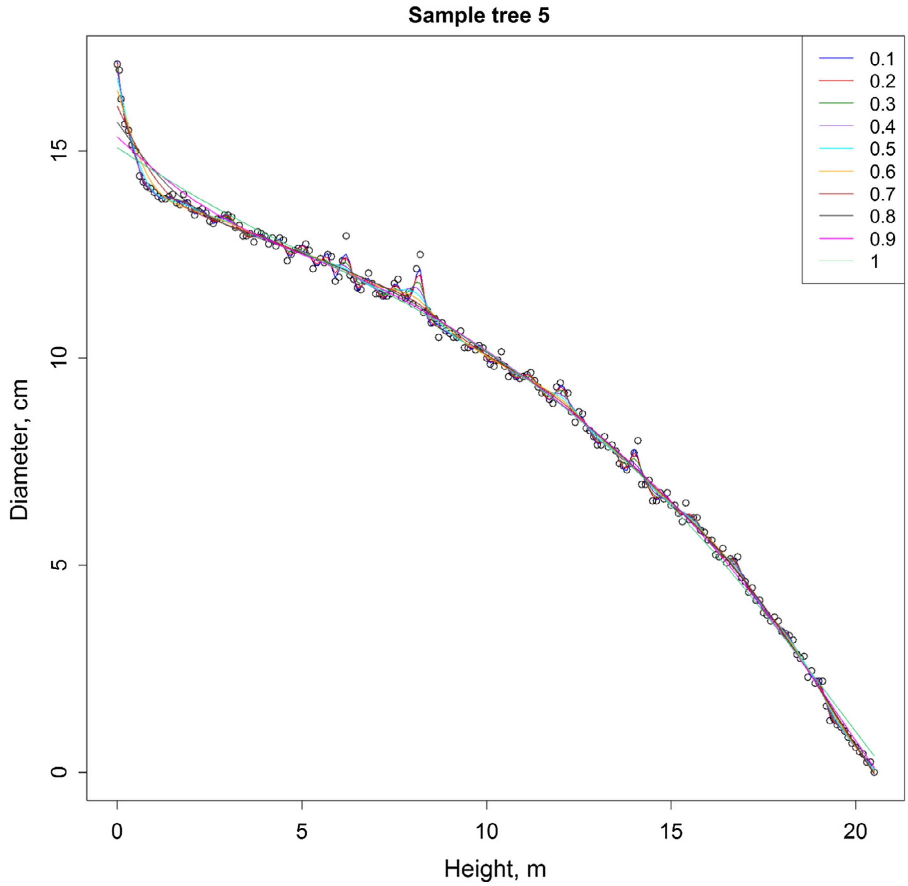


Fig. 1. An example of the effects of various smoothing parameters on the fitted cubic spline for sample tree number 5 (young birch).

$$V = \sum_{i=1}^{n} A_{m_i} h_i, \tag{1}$$

where A_m is the cross-sectional area at the middle of a stem section and h the length, i.e. 10 cm.

The standard deviation of the stem volume estimates with the various smoothing parameters varied from 0.3 dm^3 to 1.5 dm^3 between the sample trees (Table A.1), with an average of 0.6 dm^3. Smoothing parameter 0.4 described the butt part of the stem better than the parameters that smoothed the spline even more, and the standard deviation between the stem volume estimates with parameters of 0.4 and 0.6 was less than 0.6 dm^3 for all the sample trees. Therefore, smoothing parameter 0.4 was selected for estimating the stem volume from the field reference.

2.2. Terrestrial laser scanning

2.2.1. Overview of the workflow

The TLS data were collected using a phase-shift scanner Leica HDS6100 (Leica Geosystems AG, Heerbrugg, Switzerland; now Hexagon AB, Stockholm, Sweden) with high-resolution setting during the field measurements in early December 2015. Each sample tree was scanned from two sides with varying distances in order to compare single and multiple-scan setups. TLS point clouds were filtered to reduce noise and sample trees from individual point clouds were detected. When estimating tree attributes, height and diameters along a stem (i.e. stem curve) were measured automatically from the point clouds of each sample tree from various scan locations. Stem volume for each sample tree was then estimated based on the tree height and stem curve measured. The stem volume accuracies were evaluated first for the single-scan setup and based on the results, the optimal scan locations were selected to estimate stem volume with multiple scan-setups A (i.e. tree attributes were derived from separate point clouds) and B (i.e. tree-wise point clouds were combined before tree attributes were derived). In the multiple scan-setup A, the tree height and the stem curve were derived from separate point clouds. The final tree attributes were then the highest height value and the arithmetic means of diameters derived from separate point clouds. Compared to the multiple scan-setup B, where point clouds from different scan locations were first combined and tree attributes were derived from the combined point clouds. Finally, the accuracies of stem volume estimates from both multiple-scan setups were evaluated, and the three approaches compared. The workflow of the TLS data processing is demonstrated in Fig. 2 and the specific details can be found in the Sections 2.2.2 and 2.2.3.

2.2.2. Terrestrial laser scanning data collection

The TLS data were collected with a multiple-scan setup, in which the scan locations were placed in such a way that each sample tree was scanned from two directions (opposite sides). Scan locations were selected from the two directions in which the most comprehensive point clouds would be achieved (i.e. the best possible visibility to the sample tree stems from two opposite sides). Each sample tree was also scanned from various distances to determine the optimal scanning distance for the scanner used to obtain the most accurate stem volume estimates for these types of trees. With traditional height measurement devices (i.e. varying types of clinometers), the rule of thumb is to view the tree to be measured at the distance corresponding the height to be measured (Husch et al. 2003). To understand whether this is true with a Leica phase-shift scanner used here, the scanner was placed at distances corresponding to approximately 25%, 50%, 75% and 100% of the tree height (for two opposite directions), equalling eight scan locations

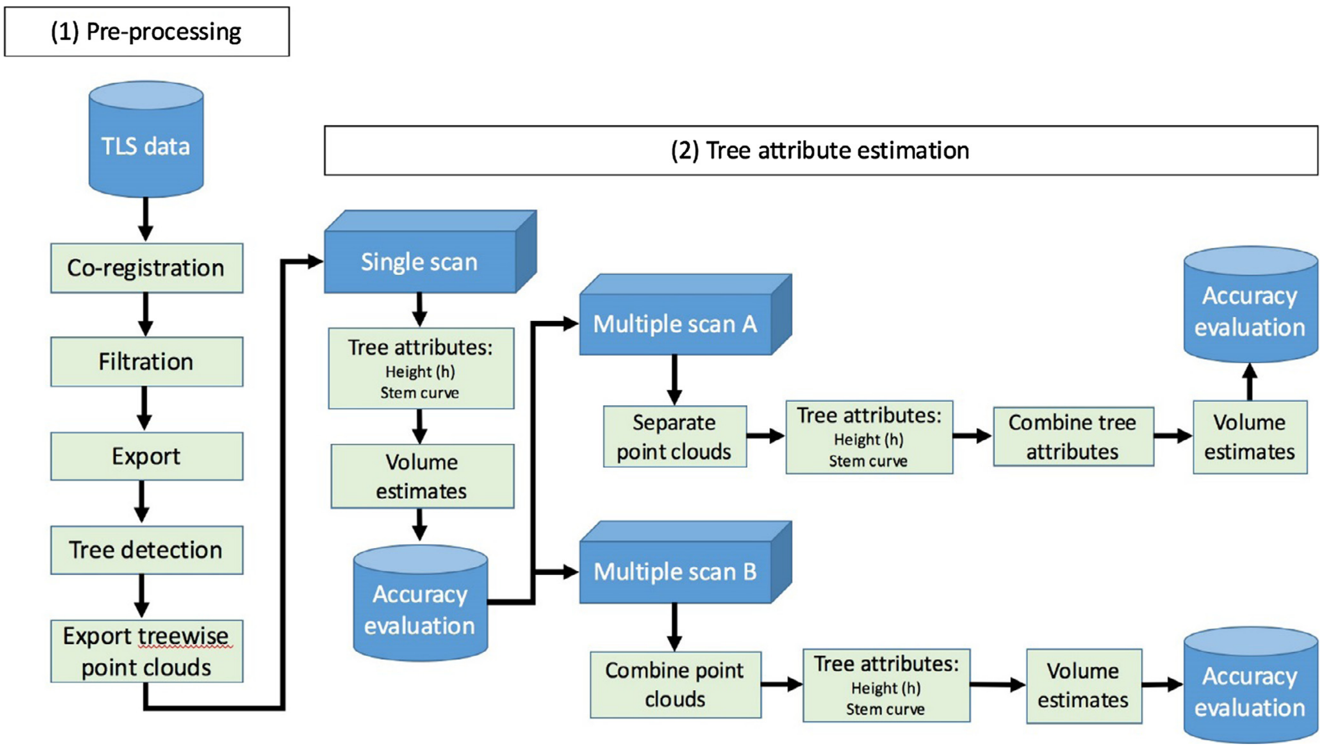


Fig. 2. Workflow of TLS data processing and estimating stem volume.

per sample tree in total. The tree height for setting up scanning locations was determined with a Vertex hypsometer. The absolute scanning distances can be found in Table A.2. Constant sized reference targets (circular with diameter of 19.8 cm) were placed around each sample tree to co-register the individual scans into one comprehensive point cloud.

For the TLS data acquisition, the location of the breast height, i.e. the 1.3-m height from the highest root collar, was marked in the field to ensure the matching between the field- and TLS-based diameter measurements. The TLS data were acquired during 3 days and the weather was windy, especially during the first day. We recorded hourly wind observations from the weather station in Iso Evo, which is located near the study site. The wind was mainly from the West, and the speed varied between 2 m/s and 6 m/s, with gusts up to 13 m/s.

The average point density of TLS data was 25,200 points per m^2 at a distance of 10 m, with a point spacing of approximately 6.3 mm (0.63 mrad angular resolution). The overall mean point spacing at the stem surface of the sample trees was 7.8 mm (corresponding to an average point density of ~16,360 pts/m^2), varying from 3.2 mm (~100,400 pts/m^2) to 12.5 mm (~6400 pts/m^2) at various scanning distances (Table 3). The data-acquisition time per each scan was approximately 3 min, and each scan included in total 5060 scan lines.

2.2.3. Terrestrial laser scanning data processing and extracting tree attributes

In the first phase (i.e. Pre-processing), individual scans of each sample tree were co-registered with accuracies varying from 0.4 mm to 1.8 mm with an overall accuracy of 1.1 mm. To remove noise, the resulting point clouds were filtered using a Z + F LaserControl (Zoller & Fröhlich GmbH, Wangen im Allgäu, Germany) with basic filtering protocols (i.e. intensity and mixed pixels). These filtered point clouds were then stored into files including data from each scan location separately (resulting 8 files per tree). The sample trees were detected from point clouds at each scan location, using the field-placed mark at the 1.3-m height, and the sample-tree specific point clouds were extracted for further analysis with a TerraScan software (Terrasolid, Helsinki, Finland).

In all three approaches (i.e. single-scan setup, and multiple-scan setups A and B), a tree height was recorded, using the maximum height value of the normalized point cloud (i.e. height above the ground) for each tree at each scan location (single scan and multiple-scan setup A) or combination (multiple-scan setup B). A stem curve was automatically derived by fitting circles at heights corresponding the heights in the reference data (i.e. in every 10 cm) along the stem (see Litkey et al., 2008; Maas et al., 2008) from either the separate point clouds (single scan and multiple-scan setup A) or the combined point clouds (multiple-scan setup B). The phase of Tree attribute estimation was conducted with the R software for all three approaches. To remove clear outlier estimates, threshold values for lower (below 1.3 m) and upper (above 1.3 m) parts of a stem were defined by analysing changes in stem tapering in the reference measurements. I.e. tapering between heights at each 10 cm in the reference measurements was calculated for all sample trees. Minimum, maximum, mean, and standard deviation were then determined for tapering below and above 1.3 m for each tree. The means of maximum tapering values among all sample trees for lower and upper parts of a stem were used to select the threshold values, i.e. 23.3 mm at lower (below the dbh) and 13.1 mm at upper (above the dbh) part of a stem. The stem diameters were excluded if they differed more than the above-mentioned thresholds from the mean of three previous stem diameters accepted. In the multiple-scan setup A, the final diameters were calculated as an average of the selected diameters from separate point clouds at specific heights. Finally, cubic spline functions were fitted to the final stem diameters to predict the missing diameters to enable estimating stem volumes.

A stem volume was estimated from the final set of stem diameters (i.e. the final stem curve obtained after fitting a cubic spline) in a manner similar to that of the stem volume estimated from the reference data (see section on Reference measurements), i.e. using Huber's formula (Eq. (1)) and summing up the volume estimates of the stem sections with lengths of 10 cm. The proportion of auto-

Table 3
Average point spacing (in mm) of individual scans at the surface of each sample tree stem at height of 1.3 m in relation to the scanning distance.

Tree ID	Scan location							
	−100%	−75%	−50%	−25%	+25%	+50%	+75%	+100%
1	11.0	8.3	5.7	2.6	2.6	5.8	7.9	10.3
2	7.9	5.5	3.7	1.7	1.8	3.9	5.6	7.5
3	14.1	10.6	7.2	3.6	3.4	7.0	10.7	14.0
4	15.8	12.7	8.1	4.0	4.0	8.2	12.4	16.3
5	13.3	10.3	6.2	3.2	3.6	6.4	9.9	14.0
6	13.8	9.8	6.7	3.6	3.5	6.6	10.4	14.1
7	8.9	7.2	5.0	2.7	2.3	4.6	6.8	9.1
8	14.8	11.0	7.2	4.3	3.8	7.4	11.1	14.8
9	12.1	9.4	6.3	3.1	3.4	6.0	9.8	12.5
MEAN	12.4	9.4	6.2	3.2	3.2	6.2	9.4	12.5

matically derived diameters along a stem (i.e. success rate) to enable fitting the cubic spline was determined for each sample tree and scan location. The accuracy of the TLS-based stem volume estimates was determined based on the absolute and relative error (difference), as well as the mean difference (Eq. (2)) and RMSE (Eq. (3)) between the stem volume based on the TLS and the reference data.

$$Mean\ difference = \frac{\sum(V_{TLS} - V_{ref})}{n}, \quad (2)$$

$$RMSE = \sqrt{\frac{\sum(V_{ref} - V_{TLS})^2}{n}}, \quad (3)$$

where V_{ref} is the stem volume based on the field reference (stem volume estimate with diameters measured in the field), V_{TLS} the stem volume estimate based on the diameters measured from the TLS point cloud, and n the number of the sample trees. The relative mean difference and RMSE were also calculated by dividing the results obtained with Eqs. (1) and (2) by the mean value from the reference data. In addition to the accuracy of TLS-based stem volume estimates, also the accuracy of tree height measured from TLS point clouds was assessed.

In addition to accuracy, we estimated time consumption for different setups and approaches (i.e. single-scan, multiple-scan A, and multiple-scan B) to compare them. We did not measure the exact time consumption for field work for various methods, rather the approaches were valued based on our assessment during the data collection.

3. Results

The main context of the present study was to evaluate the capability of TLS for acquiring the reference data required for stem volume equation development, which is important especially where these equations are unavailable. As a starting point, we needed the accuracy of TLS-based stem volume estimates from single-scan setup to compare with detailed reference data. We observed that the number of successfully measured diameters along the stem from the individual TLS point clouds with the automatic procedure affected the stem volume estimates. We first report the result regarding the measurements of tree height and diameters from the TLS data collected with single-scan setup at various scan locations and then the respective accuracies of the derived stem volume estimates. After that we present the stem volume estimates obtained with two processing approaches of multiple TLS data sets. The results for each setup were presented to enable us to deal with the practicalities regarding TLS data collection, i.e. if a single TLS scan is used, how it should be placed in relation to the tree and how multiple point clouds should be selected and processed with the scanner type used and trees studied here.

3.1. Tree height

The TLS-based measurements underestimated the tree height for every tree species, size class (young, mature and regeneration-ready) and scan location. Depending on the scan location, the underestimates varied from −2.8 m to −1.4 m (Fig. A.3a), with standard deviations varying between −2.3 m and −1.3 m. The RMSEs for the height estimates varied from 1.9 m to 3.6 m. The highest accuracy was achieved with scan location −50%, whereas the lowest accuracy for height estimates was obtained from scan location +100%.

3.2. Stem diameters with single-scan setup

It was discovered that for estimating the stem volume with single-scan setup, the sufficient proportion of automatically measured diameters along the stem (i.e. success rate) was 25%. There were no large differences between tree species in the success rate (Table A.3), although with the smallest pine (tree ID 2) the highest mean success rate of 50% was obtained; i.e. half of the stem diameters were automatically derived from the single-scan TLS data. Larger differences were found between the scanning distances: scan location −25%, resulted in the highest success rate for measuring stem diameters automatically from the TLS point cloud (Table A.3 and Fig. A.3b).

3.3. TLS volume with single-scan setup

We obtained stem volume estimates for all the sample trees with the single-scan setup at scan locations between −50% and +50% (Table A.4). Longer scanning distances resulted in insufficient diameter values for fitting cubic spline functions (success rate <25%, compare Tables 6 and 7), and therefore estimating stem volumes was not reasonable. I.e. at least 25% from the maximum number of diameters measured from the reference data were required to enable the cubic spline fitting for stem volume estimation. Estimating stem volumes from distances of −100% and +100% was especially challenging, due to the limited visibility, but also because the point density at the trunk of a sample tree was not sufficient for producing successful diameter measurements. Based on the overall point spacing presented in Table 3, the minimum point spacing for diameter measurements and stem volume estimates was 12.7 mm corresponding ~6200 points/m^2.

The mean difference in stem volume estimates varied between $-39.0\ dm^3$ and $34.3\ dm^3$, corresponding to relative errors from −8.1% to 6.1% (Table 4). Scan location −25% resulted in the smallest relative mean difference (0.8%). When the standard deviations of the estimation error were compared, the smallest relative standard deviation of the estimation error were obtained at scan location +75% (Fig. 3). It should be noted, however, that from scan location

+75% there were only seven stem volume estimates because sufficient number of successfully measured stem diameters (i.e. 25%) was not possible to obtain for all sample trees. The smallest relative standard deviation of the estimation error (7.3%) was obtained with the TLS data from scan location -25% from those data sets that resulted in stem volume estimates for all sample trees.

The absolute RMSE for the stem volume estimates varied between 3.2 dm^3 and 69.6 dm^3, and the highest accuracy was obtained from scan location +100% (Table 5 and Fig. 4). However, this is not fully comparable because, as mentioned before, it was possible to provide successful stem volume estimates for only one sample tree from this scan location due to the limited number of stem diameter observations. Scan location +25% provided the most accurate results (relative RMSE of 6.0%) at those scan locations that resulted in sufficient TLS data for stem volume estimates for all sample trees.

Three large estimation errors for Scots pine were observed, of which two are from the regeneration-ready and one from the mature pine (Fig. A.4). The stem form of the regeneration-ready pine was found non-circular (Fig. 5) which caused uncertainty in the estimates. The wind, on the other hand, was the strongest while the mature pine was scanned and the stem can be expected to sway because of the wind during the scanning. This can have caused error in the diameters measured from the point cloud and introduced uncertainty in the stem volume estimate. The smallest variation in the relative estimation error was for birch and relative RMSE for spruce (Table 5 and Fig. A.4). There were no clear differences in estimation errors between the size classes.

3.4. Estimating stem volume with multiple-scan setup

3.4.1. Selecting scan locations and deriving stem diameters

We selected scan locations between −50% and +50% based on the results presented above to investigate the effect of multiple scans on the accuracy of stem volume estimates. The scan locations were coded as from A to D corresponding respective scan locations (Fig. 6).

Success rate of automatically derived stem diameters increased by approximately 15–20% when two point clouds from various scan locations were employed compared to single-scan setup (Table 6 and Fig. 7). The success rate was higher when diameters were derived from combined point clouds (between 58.7% and 62.45) (i.e. multiple-scan setup B, see Section 2.2) compared to separate processing of multiple point clouds (success rate from 51.1% to 55.2%) (i.e. multiple-scan setup A). The stem volume estimates with these two processing methods are presented in the following sections.

3.4.2. Stem volume estimates from separately processed point clouds

When utilizing two TLS point clouds but deriving stem diameters separately from them (i.e. Multiple-scan setup A, see Section 2.2), stem volumes were mainly overestimates, only combination of scans B and D (i.e. scan locations −25% and +50%) resulted in an underestimation of 7.7 dm^3 (1.3%) (Table 7). The combination of both scans at 25% of tree height (i.e. scan locations B and C) produced the smallest estimation error of 0.5 dm^3 (0.9%). The smallest relative standard deviation of estimated volume error was, however, achieved with a combination of scan locations −25% and +50% (i.e. scan locations B and D) (Fig. 8). The actual stem volume estimates are presented in Table A.5.

A combination of both scan locations at 25% of tree height (i.e. scan combination BC) also resulted in the smallest RMSE, i.e. 18.1 dm^3 (4.6%) (Table 8 and Fig. 9). Stem volume estimates for Scots pine were the most inaccurate with all scan combinations. For the smallest trees (i.e. size class "young") results were similar among the scan combinations, whereas more inconsistencies in RMSEs were observed for other size classes when comparing scan combinations.

3.4.3. Stem volume estimates from combined point clouds

When point clouds from various scan locations were combined and diameters were derived from these combined point clouds (i.e. Multiple-scan setup B, see Section 2.2), the stem volumes were overestimated with all scan combinations when examining the

Table 4
Absolute (dm^3, in upper table) and relative (%, in lower table) errors of the TLS-based stem volume estimates for each sample tree at various scanning distances. N represents the number of successfully estimated stem volumes.

Tree ID	Scan location							
	−100%	−75%	−50%	−25%	+25%	+50%	+75%	+100%
1	33.4	−29.6	55.9	39.9	31.6	−19.0	−8.8	*
2	−0.9	2.8	2.7	1.8	−1.7	−3.4	−3.9	−3.2
3	*	−6.7	17.4	−46.9	−11.1	−0.9	−13.8	*
4	*	44.5	30.2	22.8	−28.3	−59.9	−71.0	*
5	*	*	8.8	6.8	7.3	−3.1	*	*
6	*	−36.8	−2.9	7.4	6.2	−16.5	−33.6	*
7	−25.0	−24.3	−14.6	−12.6	−32.8	−23.6	*	*
8	*	15.5	197.0	−37.6	−43.9	−212.7	−125.0	*
9	*	33.0	13.9	3.6	3.0	−9.9	−17.2	*
MEAN (dm^3)	2.5	−0.2	34.3	−1.6	−7.7	−38.8	−39.0	−3.2
N	3	8	9	9	9	9	7	1
1	13.3	−11.8	22.2	15.9	12.6	−7.5	−3.5	*
2	−1.5	4.4	4.3	2.9	−2.6	−5.4	−6.1	−5.0
3	*	−1.2	3.0	−8.2	−1.9	−0.2	−2.4	*
4	*	5.6	3.8	2.9	−3.5	−7.5	−8.9	*
5	*	*	5.5	4.3	4.6	−1.9	*	*
6	*	−11.2	−0.9	2.3	1.9	−5.0	−10.3	*
7	−17.9	−17.5	−10.5	−9.1	−23.5	−17.0	*	*
8	*	1.9	24.0	−4.6	−5.4	−25.9	−15.3	*
9	*	8.4	3.5	0.9	0.8	−2.5	−4.4	*
MEAN (%)	−2.0	−2.7	6.1	0.8	−1.9	−8.1	−7.3	−5.0
N	3	8	9	9	9	9	7	1

* Diameter success rate (%) <25%; therefore, stem volume estimation was unsuccessful.

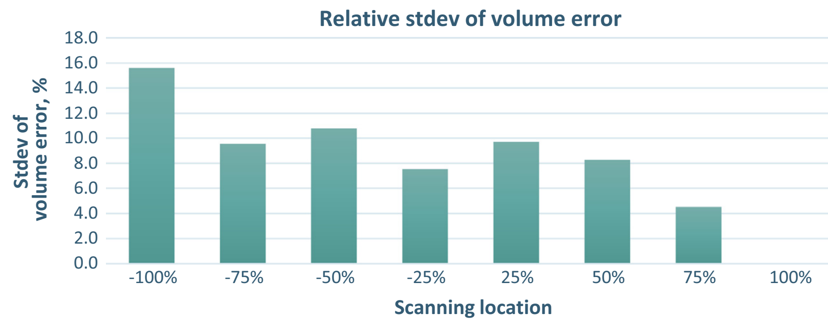


Fig. 3. Relative standard deviations of the estimation errors of the TLS-based stem volumes at various scan locations with single-scan setup. *100% value is NA → only one (1) successful volume estimate.

Table 5
Absolute (dm^3) and relative (%) root-mean-square errors (RMSEs) of stem volume estimates derived from TLS at various scan locations. N represents the number of successfully estimated stem volumes.

	RMSE								
	dm^3								
	−100%	−75%	−50%	−25%	+25%	+50%	+75%	+100%	MEAN
Overall	24.1	27.8	69.6	25.8	23.6	74.6	56.5	3.2	38.2
Scots pine	23.6	19.4	118.2	31.7	31.2	123.3	72.4	3.2	52.9
Norway spruce	25.0	24.0	15.4	28.1	20.1	14.8	15.6	–	20.4
Birch	–	40.8	18.3	14.4	17.2	35.9	55.6	–	30.4
Young	17.7	17.3	10.0	8.4	19.4	13.9	3.9	3.2	11.7
Mature	33.4	33.3	33.3	23.5	18.7	15.6	22.4	–	25.7
Regeneration-ready	–	27.5	115.5	37.1	30.8	127.6	83.4	–	70.3
N	3	8	9	9	9	9	7	1	6.9
	RMSE								
	%								
	−100%	−75%	−50%	−25%	+25%	+50%	+75%	+100%	MEAN
Overall	6.1	7.1	17.8	6.6	6.0	19.1	14.4	0.8	9.7
Scots pine	6.2	5.1	31.3	8.4	8.3	32.6	19.1	0.8	14.0
Norway spruce	6.8	6.5	4.2	7.6	5.4	4.0	4.2	–	5.5
Birch	–	9.5	4.3	3.4	4.0	8.4	13.0	–	7.1
Young	14.6	14.3	8.2	6.9	16.0	11.5	3.2	2.6	9.7
Mature	10.3	10.3	10.3	7.3	5.8	4.8	6.9	–	8.0
Regeneration-ready	–	3.8	15.8	5.1	4.2	17.5	11.4	–	9.6
N	3	8	9	9	9	9	7	1	6.9

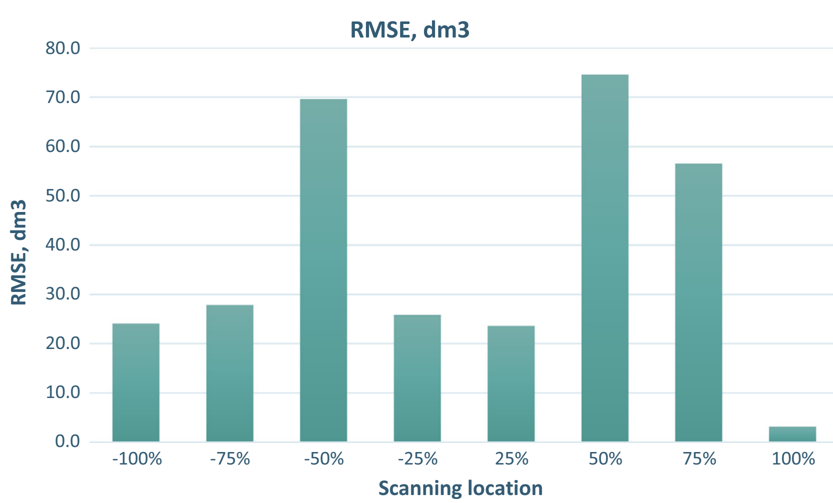


Fig. 4. Absolute root-mean-square errors (RMSEs) (dm^3) of the stem volume estimates, based on the single-scan TLS data at various scan locations.

relative estimation errors (Table 9). The smallest mean difference of $-0.9\,dm^3$ (0.4%) was obtained with the combination of scan locations −50% and +25% (i.e. scan combination of AC). The actual stem volume estimates can be found in Table A.6.

Scan combination AD (i.e. both scan locations at 50% of tree height) resulted in the smallest relative standard deviation of the estimation error (Fig 10), whereas the combination BD, that was the best with this measure when point clouds were processed sep-

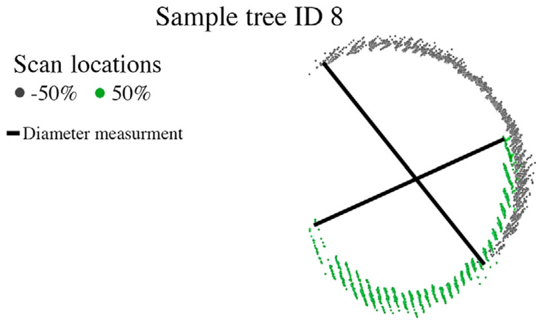


Fig. 5. Noncircular stem shape of the regeneration-ready pine, based on TLS data from scan locations −50% and +50%.

arately, produced the highest relative standard deviation of estimation error with combined point clouds (Figs. 8 and 10).

The smallest RMSE (14.6 dm^3 and 3.7%) was also obtained with the combination of the two scan locations at distance of 50% of tree height, i.e. AD (Table 10 and Fig. 11). It was also the best combination among tree species and size classes, while when processing point clouds separately (i.e. multiple-scan setup A) such trend was not visible. That combination resulted with the largest overall RMSE when point clouds were processed separately (Table 8 and Fig. 9).

3.5. Comparison between methods

To understand the differences between the results obtained with various methods, they were compared with the ability to automatically derive diameters from point clouds, relative error and RMSE. From single-scan setup results at scan locations between −50% and +50% were used in the comparison because they were utilized in multi-scan setup as well. The method with the best results was ranked as 1 whereas the method with the lowest results was ranked as 3. Although the highest success rate for deriving stem diameters was obtained when point clouds were combined before measurements (i.e. multiple-setup B), processing separately resulted in the lowest relative RMSE (Table 11). The relative error was actually the smallest with single-scan setup, but the range was the largest, therefore separately processed, i.e. multiple-scan setup A, was considered to be better. As the exact time consumption was not measured, the ranks were based on our assessments. For example, the time consumption for a single scan requires placing the tripod and scan time of approximately 3 min, this time can be expected to be doubled when two scans are used. In contrast, combining the point clouds requires placing reference targets, in addition to the tripod and the scanner, which is more time consuming.

4. Discussion

TLS showed promising results, providing stem volume estimates between 74% and 128% of destructively measured values when sufficient number (i.e. >25%) of diameters along the stem could be measured automatically. For the TLS scanner used here (Leica HDS6100) that utilizes phase-shift measurements, the tip of the tree was practically always missing in the point clouds due to occlusion caused by branches of a tree in question or an adjacent tree between the scanner and the top of a sample tree. Therefore tree height was systematically underestimated. A time-of-flight scanner that can record one or multiple returns per pulse should in theory be able to measure stem and tree top more accurately compared to a phase-shift scanner. However, as phase-shift scanners have been used when estimating stem curve (Thies et al., 2004; Pueschel et al., 2013; Liang et al., 2014) it was also tested here. The differences in measuring techniques will be analyzed and compared in detail in the future studies, especially in relation to tree height but also when deriving diameters within a tree canopy. Mean difference in the TLS-based height varied between −1.4 m and −2.8 m in this study, which is similar to the bias reported elsewhere (Hopkinson et al., 2004; Maas et al., 2008; Liang et al., 2016).

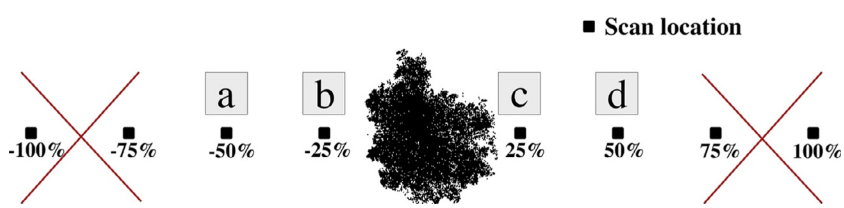


Fig. 6. Scan locations from −50% to +50% selected for further analysis as a multiple-scan setup, and recoded from A to D.

Table 6
Percentage of stem diameters successfully derived directly from the TLS data with the automatic procedure (i.e. success rate, %) with single- and multi-scan setups. Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

Tree ID	Single-scan setup				Multiple-scan setup							
					Diameters derived from separate point clouds (A)				Diameters derived from combined point clouds (B)			
	Scan location				Scan location				Scan location			
	A	B	C	D	AC	AD	BC	BD	AC	AD	BC	BD
1	29.2	39.2	50.3	45.0	51.5	46.2	53.2	47.4	62.0	63.2	62.0	62.6
2	56.5	58.1	50.8	46.0	64.5	64.5	64.5	66.1	74.2	74.2	74.2	74.2
3	44.1	40.5	37.9	41.0	46.3	48.0	44.1	44.9	53.3	50.7	56.4	56.4
4	45.9	48.9	45.6	38.9	51.9	48.9	54.4	51.9	60.0	59.6	60.4	60.0
5	51.4	53.7	51.9	37.4	57.5	56.1	60.3	58.4	66.4	63.6	67.3	66.8
6	47.7	55.0	50.5	31.8	57.7	51.4	60.5	55.5	72.3	64.1	72.3	64.5
7	44.7	49.3	31.3	26.7	48.7	48.7	54.7	54.0	59.3	46.7	51.3	52.0
8	50.8	55.0	53.3	42.9	58.3	53.8	63.3	62.5	62.9	61.3	66.7	62.9
9	35.1	33.2	35.1	32.7	44.2	42.8	41.8	40.9	44.2	44.7	51.0	49.5
MEAN	45.0	48.1	45.2	38.0	53.4	51.1	55.2	53.5	61.6	58.7	62.4	61.0

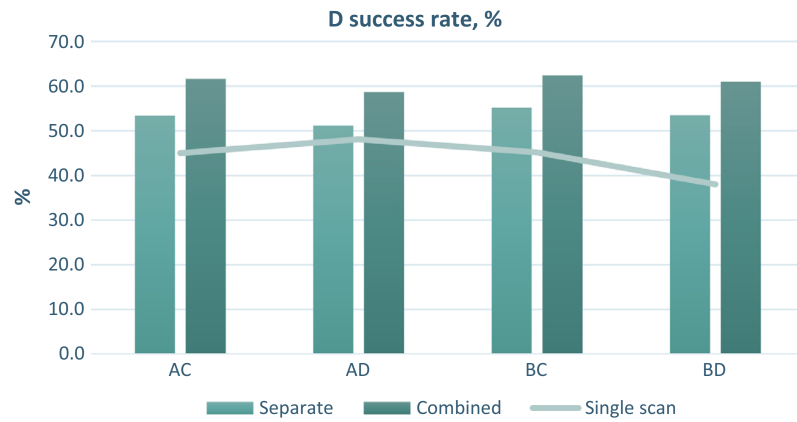


Fig. 7. Mean success rates of automatically derived stem diameters from TLS data at varying scanning distances and setups. Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

Table 7
Absolute (dm^3) and relative (%) errors of the TLS-based stem volume estimates for each sample tree at various scan combinations when point clouds were processed separately (i.e. multiple-scan setup A). Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

Tree ID	dm^3				%			
	AC	AD	BC	BD	AC	AD	BC	BD
1	37.4	−5.2	35.8	−1.5	14.9	−2.1	14.2	−0.6
2	1.4	0.9	0.0	−0.3	2.3	1.4	0.0	−0.5
3	16.6	22.0	−23.0	−6.1	2.9	3.8	−4.0	−1.1
4	8.6	−3.2	6.1	1.9	1.1	−0.4	0.8	0.2
5	10.0	9.5	8.7	8.7	6.2	5.9	5.4	5.4
6	7.8	1.8	12.4	6.9	2.4	0.5	3.8	2.1
7	−16.5	−14.0	−13.6	−13.1	−11.9	−10.1	−9.8	−9.4
8	65.1	114.0	−26.0	−65.7	7.9	13.9	−3.2	−8.0
9	11.8	10.8	4.3	−0.1	3.0	2.8	1.1	0.0
MEAN	15.8	15.2	0.5	−7.7	3.2	1.8	0.9	−1.3

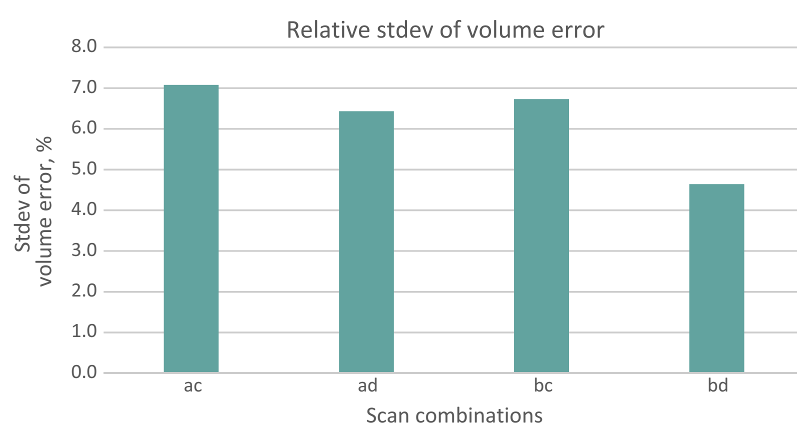


Fig. 8. Relative standard deviations of the estimation errors of the TLS-based stem volumes with various scan combinations when point clouds were processed separately (i.e. multiple-scan setup A). Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

However, underestimations in tree heights did not explicitly affect the accuracy of TLS-based stem volume estimates in our data set. Sufficient number of successfully derived stem diameters from the TLS data (i.e. >25%) allowed estimation of the stem volume with stem sections 10 cm in length also with single-scan setup. However, there clearly is a need for further study of the optimal measurement interval of diameters. The TLS data processing presented here for three approaches, is not scanner-specific and therefore possible to utilize for other scanner types (i.e. using either phase-shift or time-of-flight measuring principle) and manufacturers. However, the most influential parameter of our analysis was the threshold value for accepting or rejecting an automatically measured diameter along the stem. The values selected (i.e. 23.3 mm for below and 13.3 mm for above the dbh) were based on analysing stem tapering in the reference data, and may be sensible of the data at hand (i.e. stem forms). The selected threshold values were not presented as the optimal option for any tree species or stem form, but should be analysed further to understand their specificity to site, species, and stem form. For being able to state applicability of these parameter values, thorough sensitive analysis is required, which will be covered in our future studies. The precision of 0.1 mm can be seen as a weakness, as the process should

Table 8
Absolute (dm^3) and relative (%) root-mean-square errors (RMSEs) of stem volume estimates derived from separately processed TLS point clouds (i.e. multiple-scan setup A) at various scan combinations. Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

	RMSE									
	dm^3					%				
	AC	AD	BC	BD	MEAN	AC	AD	BC	BD	MEAN
Overall	27.0	39.3	18.1	22.7	26.8	6.9	10.0	4.6	5.8	6.8
Scots pine	43.4	65.9	25.5	37.9	43.2	11.5	17.4	6.8	10.0	11.4
Norway spruce	15.2	16.3	15.7	8.3	13.9	4.1	4.4	4.3	2.3	3.8
Birch	8.8	5.9	9.4	6.5	7.7	2.1	1.4	2.2	1.5	1.8
Young	11.2	9.8	9.3	9.1	9.9	9.2	8.1	7.7	7.5	8.1
Mature	23.1	7.0	22.0	4.1	14.1	7.1	2.2	6.8	1.3	4.4
Regeneration-ready	39.1	67.1	20.4	38.1	41.2	5.4	9.2	2.8	5.2	5.7

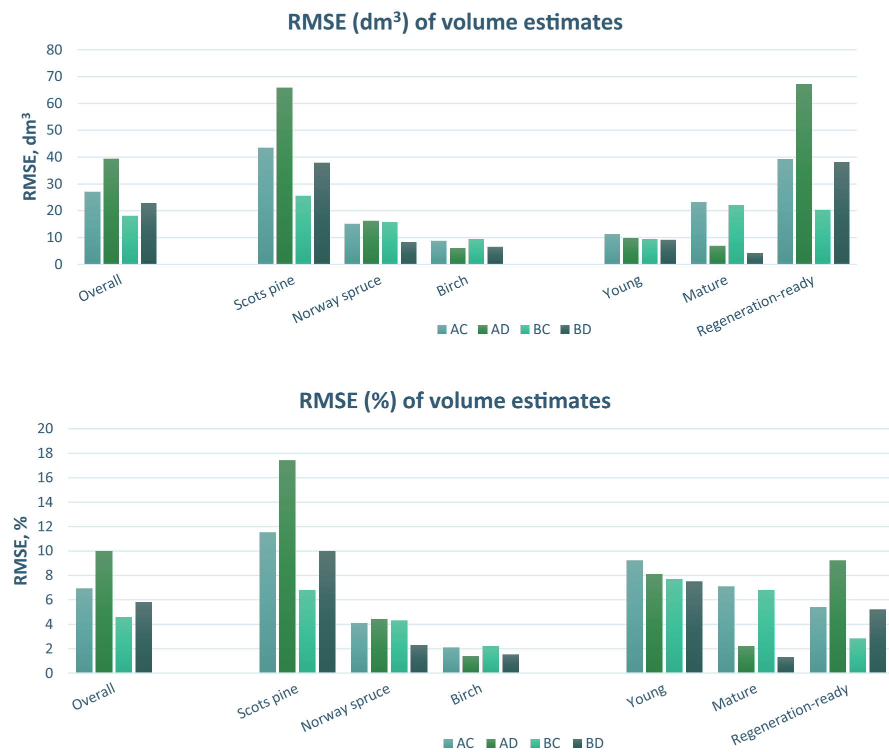


Fig. 9. Both absolute (dm^3) and relative (%) root-mean-square errors (RMSEs) of the stem volume estimates, based on the separately processed TLS data (i.e. multiple-scan setup A) at various scan combinations, tree species and size class. Scan locations A = −50%, B = −25%, C =+25%, D = +50%.

Table 9
Absolute (dm^3) and relative (%) errors of the TLS-based stem volume estimates for each sample tree at various scan combinations when point clouds were combined (i.e. multiple-scan setup B). Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

Tree ID	dm^3				%			
	AC	AD	BC	BD	AC	AD	BC	BD
1	20.5	13.8	45.4	73.0	8.1	5.5	18.1	29.0
2	1.3	1.9	3.3	4.2	2.0	3.0	5.2	6.5
3	7.4	−4.4	10.6	−2.4	1.3	−0.8	1.8	−0.4
4	39.9	23.1	41.4	16.4	5.0	2.9	5.2	2.1
5	9.0	6.8	10.7	8.5	5.6	4.2	6.6	5.3
6	12.4	2.6	25.8	8.4	3.8	0.8	7.9	2.6
7	−6.5	−5.5	0.3	4.8	−4.7	−3.9	0.2	3.5
8	−45.1	32.0	57.3	160.5	−5.5	3.9	7.0	19.6
9	−46.5	7.0	6.4	45.0	−11.9	1.8	1.6	11.5
MEAN	−0.9	8.6	22.3	35.4	0.4	1.9	6.0	8.8

not be this sensitive to be generalized. However, we do not claim these threshold values can be generalized directly to other data sets, merely our aim was to advance the research from TLS-based diameters to stem volume and test the effect of scan location. The threshold value of 25% for successfully measured diameters along the stem was selected during the analysis when fitting the cubic spline was not possible with lower success rates. All these parameters should be tested with a larger data set with variety of stem forms of the three species (i.e. Scots pine, Norway spruce and birch), and we will continue testing these parameters in our future studies

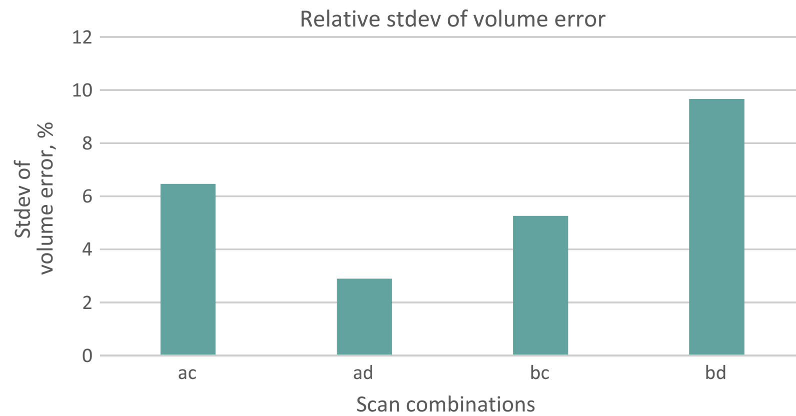
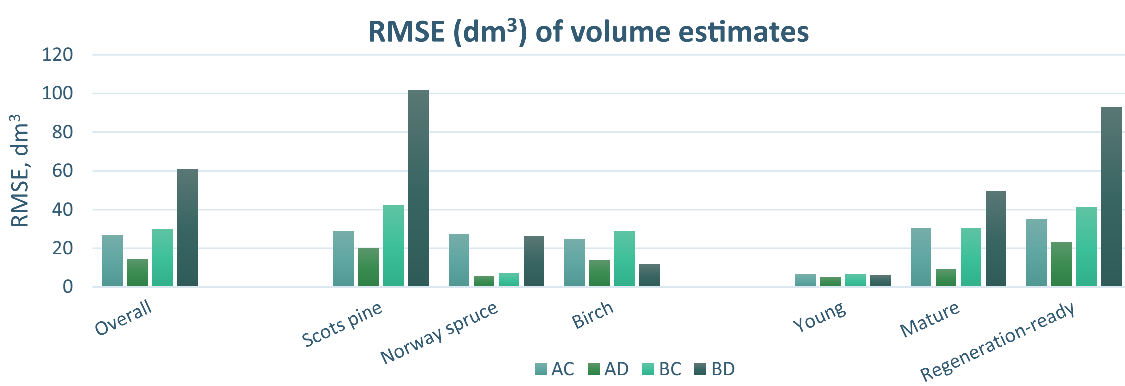


Fig. 10. Relative standard deviations of the estimation errors of the TLS-based stem volumes with various scan combinations when point clouds were combined (i.e. multiple-scan setup B). Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

Table 10
Absolute (dm^3) and relative (%) root-mean-square errors (RMSEs) of stem volume estimates derived from TLS at various scan combinations when point clouds were combined (i.e. multiple-scan setup B). Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

	RMSE									
	dm^3					%				
	AC	AD	BC	BD	MEAN	AC	AD	BC	BD	MEAN
Overall	27.0	14.6	29.8	61.1	33.1	6.9	3.7	7.6	15.6	8.5
Scots pine	28.6	20.2	42.2	101.8	48.2	7.6	5.3	11.2	26.9	12.8
Norway spruce	27.5	5.7	7.1	26.2	16.6	7.5	1.6	1.9	7.1	4.5
Birch	24.7	14.0	28.8	11.7	19.8	5.8	3.3	6.7	2.7	4.6
Young	6.5	5.2	6.5	6.1	6.1	5.3	4.2	5.3	5.0	5.0
Mature	30.2	9.1	30.4	49.7	29.9	9.3	2.8	9.4	15.4	9.2
Regeneration-ready	35.0	23.0	41.2	93.1	48.1	4.8	3.1	5.6	12.8	6.6



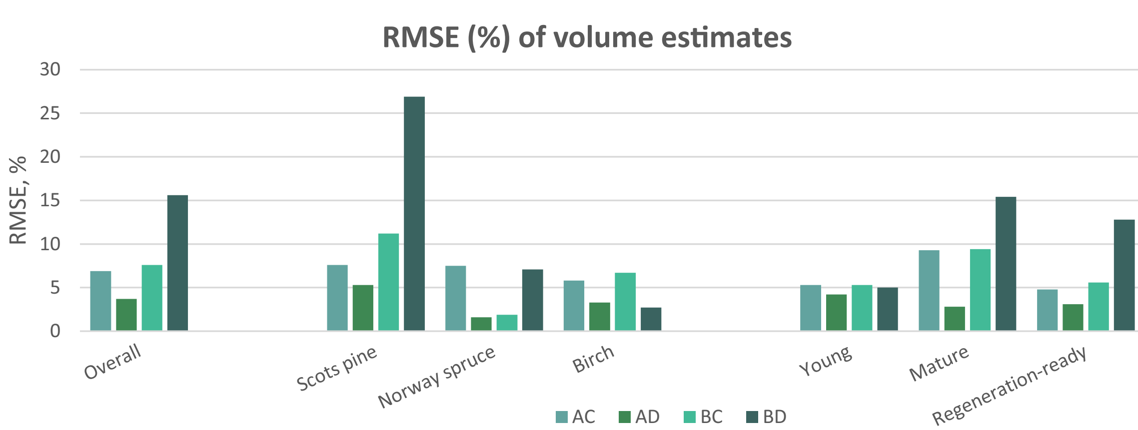


Fig. 11. Absolute (dm^3) and relative (%) root-mean-square errors (RMSEs) of the stem volume estimates, based on the combined TLS data (i.e. multiple-scan setup B) at various scan combinations, tree species and size class. Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

Table 11
Comparison between single- and multi-scan setups.

	Single-scan setup		Multiple-scan setup			
			Diameters derived from separate point clouds (A)		Diameters derived from combined point clouds (B)	
	Mean	Rank	Mean	Rank	Mean	Rank
Success rate of automatically derived diameters	44.1%	3	53.3%	2	60.9%	1
Relative error	−0.8% (Range 14.2%)	2	1.15% (Range 4.5%)	1	4.3% (Range 8.4%)	3
RMSE%	12.4%	3	6.8%	1	8.5%	2
Time consumption of data collection	Less than 10 min	1	Less than 20 min	2	20–30 min	3

to determine the generality of the thresholds. Another option for the success rate would be to test varying measuring interval for diameters, i.e. more intense interval for the visible parts of a stem and measuring all possible diameters within a canopy where more occlusion exists (possibly no systematic interval can be found).

Nicoletti et al. (2015) found no differences between stem volume estimates at varying measurement distances. Our results contrasted with those of Nicoletti et al. (2015), because the error in the stem volume estimates from the various scan locations and thus distances were in fact dissimilar. Our aim was to understand whether a Leica scanner, using phase-shift measuring principle, should be placed at the distance equal to the tree height, as it is instructed with clinometers, or closer to a tree. We were not aiming for an exact distance (or percentage of a tree height) but merely comprehend whether there is a difference between scan distances and identify an approximate scale (i.e. distance corresponding a tree height, distance corresponding roughly half of a tree height, or closer to a tree) for placing the scanner. Estimating the stem volume was not possible from scan locations of 75% and 100% of tree height, because there were not enough successfully measured stem diameters available (see Tables 4 and A.4). The limit of 25% of the successfully measured stem diameters is very dependent on the density of the diameters measured (every 10 cm in this case) but also on scanning distance, and probably a scanner type used. With shorter scanning distances, the laser beam needs to travel through more canopy structure to reach the stem which can result in less observations from the stem. Higher resolution setting of a scanner could improve the point density at a tree stem from longer distances but it would also increase the amount of scanning time. In addition to scanning time (i.e. approximately 3 min per scan), the field work of TLS also included moving the scanner from one position to another as well as placing the reference targets. Based on our results, in the studied forest conditions and scanner used, we should test the effect of higher resolution on the stem volume estimates with the multiple-scan setup A. Higher resolution does not, however, remove the challenge caused by the occlusion (i.e. the tip of the tree not visible to the scanner). Therefore, the added value of increased field work (i.e. increased costs) should be clear, e.g. in more accurate tree height measurement. Further studies would be needed to assess the optimal scanning resolution at various distances to investigate the effect on the accuracy of measuring tree height. Canopy structure is more favourable at mid-ranges considering the beam direction in deriving stem diameters. On the other hand, the point density is reduced and strength in beam signal decreased at large scanning distances that decrease the number of successful stem volume estimates.

When multiple scans were tested, the maximum scanning distance was at 50% of tree height based on the findings from single scan setup. Auspicious results were obtained with a scanning distance of 25% of tree height; thus, we suggest this distance to be employed if only a single-scan approach with a Leica phase-shift scanner is used for similar stem forms with the sample trees presented here. Results imply that a scanning distance of 25% of tree height should also be included when multiple scans with a similar scanner are utilized for these types of stem forms. The combination of both scan locations at the distance of 25% of tree height resulted in the most accurate stem volume estimates when point clouds were processed separately (i.e. the multiple-scan setup A).

When two TLS scans were utilized in estimating stem volumes, size class "young" (i.e. dbh between 10 cm and 16 cm) resulted in similar results among scan combinations, with both multiple-scan setups A and B, whereas more variation was observed with two other size classes. It can be that the stem form of the smallest trees is more consistent compared to mature and regeneration ready trees. Although, higher accuracies were obtained for mature and regeneration-ready trees when point clouds were processed separately (i.e. multiple-scan setup A), there was more inconsistencies among the scan combinations than for the smallest trees. For more comprehensive conclusions, larger data sets with wider stem form variability is required.

The standard deviations of the relative stem-volume-estimation error, which takes the tree size into account, varied between 7.6% and 10.8% with single-scan setup when only scan locations between −50% and +50% were taken into account. It was possible to decrease the mean standard deviation of the relative estimation error with both multiple-scan setups A and B by approximately 3%. It can be interpreted that if the standard deviation of the relative estimation error were close to zero, there would be no wide variation in estimation errors, regardless of the tree species and size. However, we did not observe this in our results, and therefore it is challenging to assess how much the forest structure and occlusion in the TLS data in addition to stem form and scanner used affected the stem volume estimates. It should be noted that scanning distance affects the point density of the TLS data, therefore future research should include investigations regarding the effect of scanning resolution on stem volume estimates: point densities can be similar but scanning time and visibility can differ greatly with varying scanning distance and resolution. Future studies should also focus on investigating the significance of tree species, size and forest structure to provide guidelines for TLS data collection under various forest conditions, but also with different scanner types.

For the regeneration-ready pine there were two clear outlier errors, both from distances of 50% of the tree height, one an overestimate of 197.0 dm^3 (24.0%) and the other an underestimate of 212.7 dm^3 (25.9%), when single scans were employed. These were mainly caused by the non-circular shape of the stem and small variations in scanning directions. Although the visibility was favourable and it was possible to measure the diameters automatically, there were anomalous cross-sectional stem shape that resulted in deviant stem volume estimates (see Fig. 5). Unfortunately this was not observed with the field references, because they were not necessarily measured from the same directions as the TLS data. A diameter can be derived from circumference of a stem with a diameter tape. Diameter tapes, however, assume circular cross section of a tree therefore they overestimate a diameter of a non-circular stem (Husch et al., 2003). To detect non-circular stem form, the arithmetic mean of two diameters measured with calipers perpendicular to each other is often used (Husch et al., 2003), therefore they were also used in this study. Nevertheless, diameter tapes do enable measurements from trees with diameters >60 cm, whereas calipers are commonly used for diameters smaller than that (Husch et al., 2003). The traditional allometric models (e.g. Laasasenaho, 1982) include diameters instead of circumference when estimating stem volume. However, defining the exact cross-sectional areas, instead of diameters and therefore assumptions on circular stem form, along a tree stem could enhance the utilization of the full potential of TLS in estimating a stem volume. TLS position, however, is one source of uncertainty and introduced variation in the diameter measurements. To assess this, we used two scan locations for each relative distance to assess the accuracy of TLS-based volume estimates with a Leica scanner using phase-shift measuring principle. By using multiple point clouds it was possible to reduce the error in stem volume estimates, and there was no large difference in relative error between separately processed (from −8.0% to 13.9%) or combined (from −5.5% to 19.6%) point clouds. Our future investigations will include how measuring cross-sectional area along the stem instead of diameters affect the results.

It should be noted that the reference data (i.e. the interval of determining diameters and volume of stem sections) in our study were considerably more detailed than in recent studies where the stem volume was estimated with TLS data (Kankare et al., 2013; Liang et al., 2014). Dassot et al. (2012) found that their sampling interval of 2 m were not the best reference for stem volume estimates. Therefore our interval for diameter measurements was 0.1 m, from both field reference and TLS point clouds. The reference volume in Kankare et al. (2013) and Liang et al. (2014) was determined based on stem sections with a length of 1 m. Kankare et al. (2013) measured diameters along the stem (i.e. the stem curve) manually from the TLS point cloud and obtained a relative bias of 0.67% for the stem volume estimate, and Liang et al. (2014) obtained a bias of $-5.87\ dm^3$ for stem volume estimates with an automatically derived stem curve from the TLS data. However, Astrup et al. (2014) used stem volume obtained with harvester measurements with same interval that was used here, i.e. 10 cm, as their reference data, and reported a mean difference of $35.65\ dm^3$ for the stem volume estimates. Our data sets were substantially smaller than in the previous studies mentioned and we can not necessarily generalize our results to larger context. Nevertheless, we were able to achieve an overall mean difference of $-3.5\ dm^3$ (−0.8%), which is similar to above-mentioned studies, for the TLS-based stem volume estimates at scan locations from −50% to +50%, when single-scan setup was utilized. Pueschel et al. (2013) measured diameters along stem in every 20 cm until height of 10 m, but they used a spline function to obtain the diameters with an interval of 5 cm, and reported an error between −34% and 44% when data from a single TLS scan were used.

Our sample size, and therefore the variety of stem forms, was too small to draw decisive conclusions on the differences in stem volume estimates between tree species or size classes. Even though the resulting stem volume estimates for the regeneration-ready and mature pines were less accurate than those for spruce and birch, the difference in relative RMSE was only approximately five percentage points between tree species with this data set, when utilizing single-scan setup. In addition, the results were improved when two point clouds from various scan locations were employed: the relative RMSE of the TLS-based stem volume estimates varied between 4.6% and 10.0%, and the corresponding relative mean differences ranged from −1.3% to 3.2% with TLS data when two point clouds were processed separately (i.e. multiple-scan setup A). Pueschel et al. (2013) compared single and a merged scans and reported an error ranging from −2% to 6% when TLS scans were merged (compared to the error between −34% and 44% from single scans). To assess the overall bias in the TLS-based stem volume estimates, larger samples with varying stem forms for reference are required. In addition, comparison between TLS measuring principles, i.e. phase shift and time-of-flight, need to be assessed together. Only after this can the suitability of TLS in collecting data for updating existing or developing new stem volume equations with TLS be fully evaluated. The sample size for developing stem volume equations has varied between studies (Zianis et al., 2005), but with TLS data larger samples could be obtained with reliable stem volume estimates. In addition, TLS would enable incorporation of variability (e.g. tree species, size) in a sample in a more cost-efficient manner than traditional destructive methods. However, selecting the scan locations plays a major role in deriving stem volume estimates from TLS data, and thus the stem visibility should be the primary target in placing the scanner.

5. Conclusions

We presented here our first results of collecting and using TLS data for building empirical stem volume equations. Here, we demonstrated the expediency of a phase-shift TLS in deriving the stem volume of a single tree of various species and sizes. The results clearly showed the importance of selecting the scan location for these tree types and this particular scanner. If a sufficient number of successful diameter measurements (i.e. success rate) were not achieved from the TLS data, volume modelling was not possible. This critical threshold value for the success rate was found to be 25% but is expected to vary, depending on the diameter measurement interval and distribution of the successfully measured diameters along the stem as well as forest conditions and scanner type. When only a single scan was used, the most promising results were obtained with a scanning distance of 25% of tree height.

The accuracy and precision of stem volume estimates were improved, when two TLS point clouds were utilized. We selected scan locations at 25% and 50% of tree height, as they provided stem volume estimates for all sample trees in the previous phase (i.e. single-scan setup). When diameters along the stem were derived from separate point clouds, results were more stable; i.e. the variation in relative mean difference and RMSE of stem volume estimates were smaller (mean RMSE 6.8%) than the results obtained with combined point clouds (mean RMSE 8.5%). In addition, when point clouds are processed separately, work load in the field is lower as reference targets for co-registration of point clouds are not needed. This approach also requires less processing before the actual utilization of data set.

Stem volume estimation from TLS data has been studied actively during recent years (Pueschel et al., 2013; Astrup et al., 2014; Liang et al., 2014), and we acknowledge that nine trees, with limited range of stem forms, are not adequate for drawing comprehensive conclusions. Nevertheless, the results obtained here were similar when compared with previous studies (e.g. Kankare et al., 2013; Liang et al., 2014; Pueschel et al., 2013). Thus, the study encouraged us to continue investigations towards providing TLS data for building empirical stem volume equations. However, the true accuracy of the TLS-based stem volume estimates found should be investigated with larger datasets with more variability, especially in stem forms and varying scanner types. Future research will include questions on the accuracy required for unbiased stem volume equations and the optimal method for measuring diameters from the TLS point cloud.

Author contributions

Ninni Saarinen, Ville Kankare and Mikko Vastaranta planned the study design together with Markus Holopainen and Juha Hyyppä. Ninni Saarinen and Ville Kankare were the main authors and responsible of the data processing, analysis and accuracy assessment. Ville Luoma, Jiri Pyörälä, and Topi Tanhuanpää collected the reference and TLS data together with Ninni Saarinen, Ville Kankare, and Mikko Vastaranta. Xinlian Liang, Harri Kaartinen, Antero Kukko, Anttoni Jaakkola and Xiaowei Yu contributed writing the introduction and discussion together with Ninni Saarinen and Ville Kankare, and their ideas for TLS data collection and processing were utilized when the study was designed. The TLS instrument was provided by the Finnish Geospatial Research Institute. The paper was improved by the contributions of all authors at various stages of the analysis, writing and review process.

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Appendix A

A.1. Fitting a smoothing cubic spline to the reference data

Table A.1
Stem volume estimates (dm^3) for the sample trees from a smoothing cubic spline with varying smoothing parameter. Stdev = standard deviation, Stdev: 0.4–0.6 = standard deviation between the stem volume estimates, using smoothing parameters between 0.4 and 0.6.

Smoothing parameter	Tree ID								
	1	2	3	4	5	6	7	8	9
0.1	251.3	63.5	573.3	796.4	160.7	327.5	139.1	819.1	391.3
0.2	251.3	63.5	573.3	796.5	160.7	327.5	139.1	819.2	391.3
0.3	251.4	63.5	573.5	796.7	160.7	327.6	139.2	819.3	391.4
0.4	251.6	63.6	573.7	797.1	160.8	327.6	139.2	819.5	391.5
0.5	251.8	63.7	574.0	797.7	160.8	327.8	139.4	819.8	391.6
0.6	252.1	63.7	574.3	798.5	160.9	328.0	139.5	820.3	391.8
0.7	252.4	63.8	574.7	799.3	161.0	328.2	139.7	820.8	392.0
0.8	252.7	63.9	575.0	800.0	161.1	328.4	139.8	821.3	392.2
0.9	252.9	64.0	575.2	800.4	161.2	328.5	139.9	821.7	392.4
1.0	252.9	64.0	575.3	800.4	161.1	328.5	139.8	821.4	392.3
Stdev	0.6	0.2	0.7	1.5	0.2	0.4	0.3	0.9	0.4
Stdev: 0.4 – 0.6	0.2	0.1	0.3	0.6	0.1	0.1	0.1	0.3	0.1

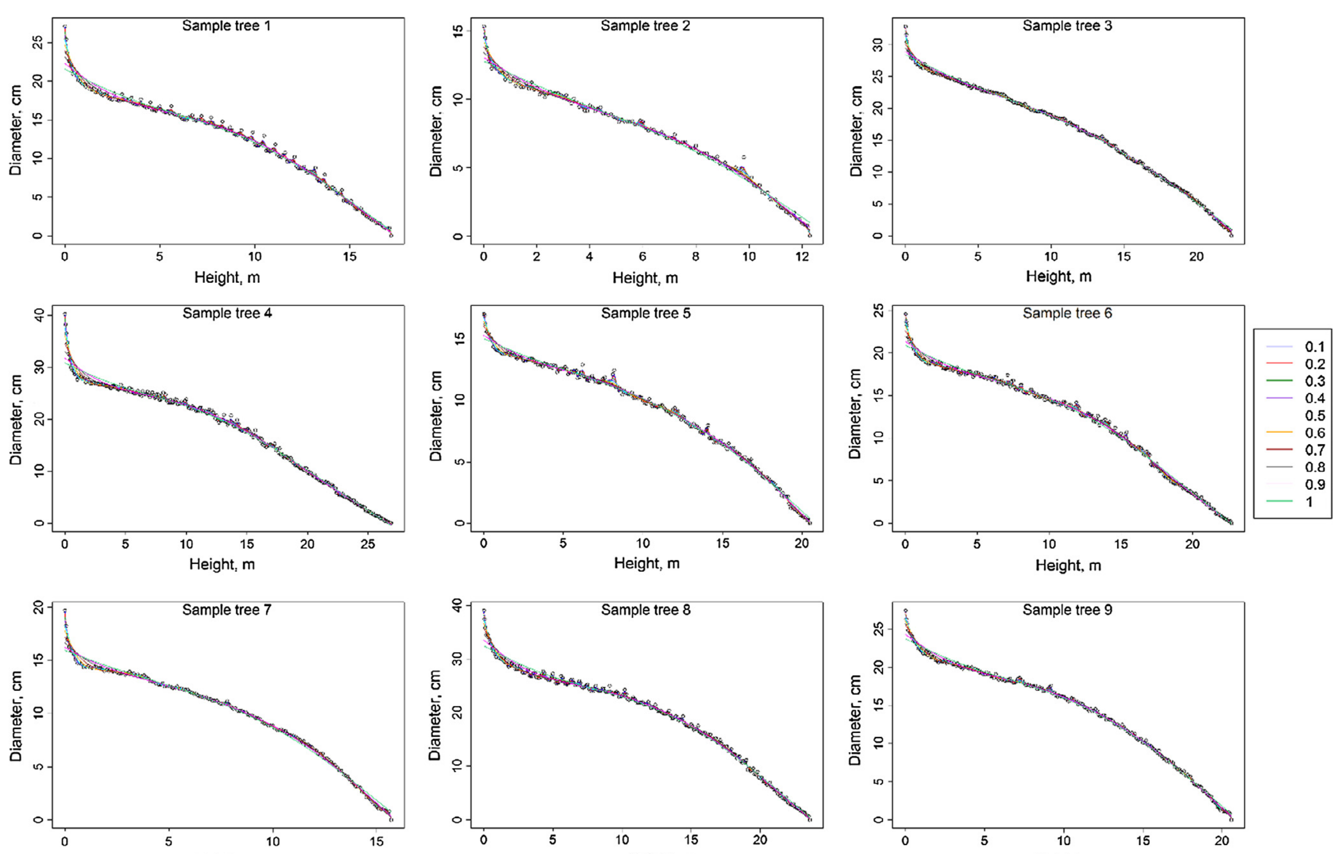

Fig. A.1. The effects of various smoothing parameters on the fitted cubic spline for all sample trees.

A.2. Details of TLS data sets

Table A.2
True scanning distances (in metres) for the sample trees, corresponding to the various percentages of tree height.

Tree ID	Scan location							
	−100%	−75%	−50%	−25%	+25%	+50%	+75%	+100%
1	16.92	12.58	8.77	4.25	4.26	8.35	12.80	16.94
2	12.01	8.75	5.83	2.9	2.92	6.03	8.63	11.6
3	22.4	16.85	11.16	5.44	5.54	11.04	16.75	22.25
4	26.46	20.41	13.85	6.9	6.51	13.23	19.93	26.15
5	21.35	16.25	10.25	5.62	5.91	10.56	15.9	21.66
6	21.62	16.56	11.04	5.74	5.88	10.61	16.3	21.92
7	14.65	11.21	7.66	4.25	3.91	7.64	11.42	14.38
8	23.92	17.57	11.56	6.57	6.29	11.9	17.72	23.72
9	19.4	15.34	10.14	5.17	5.38	9.78	15.27	20.38

A.3. Tree height and automatically derived diameters from single scans

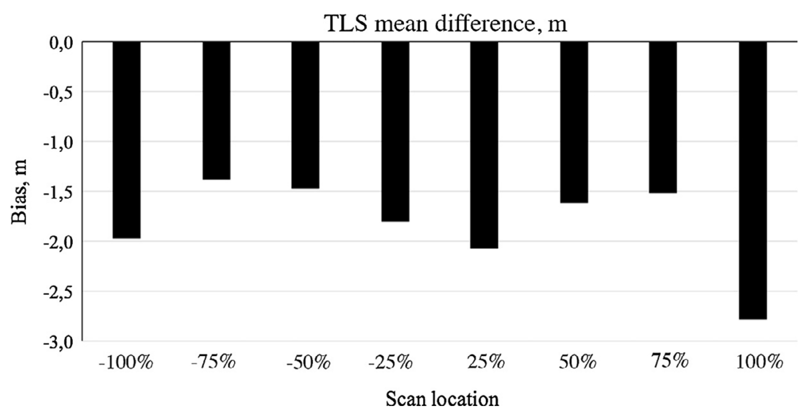

Fig. A.3a. Mean difference (m) of TLS-based height measurements at various scan locations.

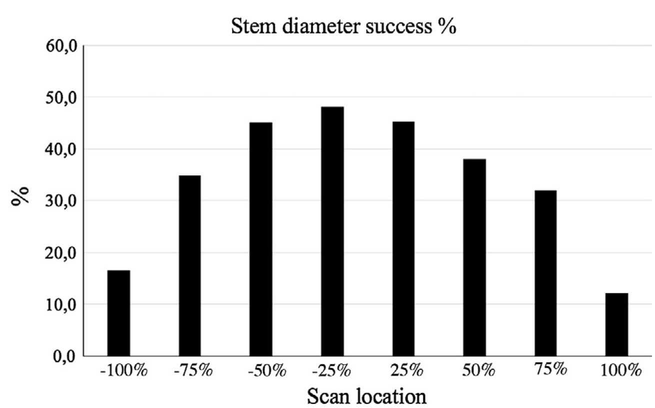

Fig. A.3b. Mean success rates of automatically derived stem diameters from TLS data at varying scanning distances when single scans were utilized.

Table A.3
Percentage of stem diameters successfully derived directly from the TLS data with the automatic procedure (i.e. success rate, %) at various scan locations when single-scan setup was utilized.

Tree ID	Scan location								MEAN
	−100%	−75%	−50%	−25%	+25%	+50%	+75%	+100%	
1	39.2	39.8	29.2	39.2	50.3	45.0	42.1	25.1	38.7
2	40.3	61.3	56.5	58.1	50.8	46.0	44.4	42.7	50.0
3	15.4	32.6	44.1	40.5	37.9	41.0	36.1	8.8	32.0
4	0.7	28.5	45.9	48.9	45.6	38.9	28.5	0.7	29.7
5	0.0	15.4	51.4	53.7	51.9	37.4	17.3	0.0	28.4
6	6.4	28.6	47.7	55.0	50.5	31.8	27.7	2.3	31.3
7	28.7	34.7	44.7	49.3	31.3	26.7	24.0	15.3	31.8
8	5.4	43.3	50.8	55.0	53.3	42.9	38.8	4.6	36.8
9	13.0	29.3	35.1	33.2	35.1	32.7	28.8	9.1	27.0
MEAN	16.6	34.8	45.0	48.1	45.2	38.0	32.0	12.1	

A.4. Stem volume with single-scan setup

Table A.4
TLS-based stem volume estimates (dm^3) for each sample tree at various scan locations with single-scan setup.

Tree ID	Scan location							
	−100%	−75%	−50%	−25%	+25%	+50%	+75%	+100%
1	285.0	222.0	307.5	291.5	283.2	232.6	242.8	*
2	62.6	66.4	66.3	65.4	61.9	60.2	59.7	60.4
3	*	567.0	591.1	526.8	562.6	572.8	559.9	*
4	*	841.6	827.3	819.9	768.8	737.2	726.1	*
5	*	*	169.6	167.6	168.1	157.7	*	*
6	*	290.9	324.8	335.1	333.9	311.2	294.0	*
7	114.3	114.9	124.6	126.6	106.5	115.6	*	*
8	*	835.1	1016.5	781.9	775.7	606.9	694.5	*
9	*	424.4	405.3	395.0	394.4	381.6	374.3	*

[*] Diameter success rate (%) <25%; therefore, stem volume estimation was unsuccessful.

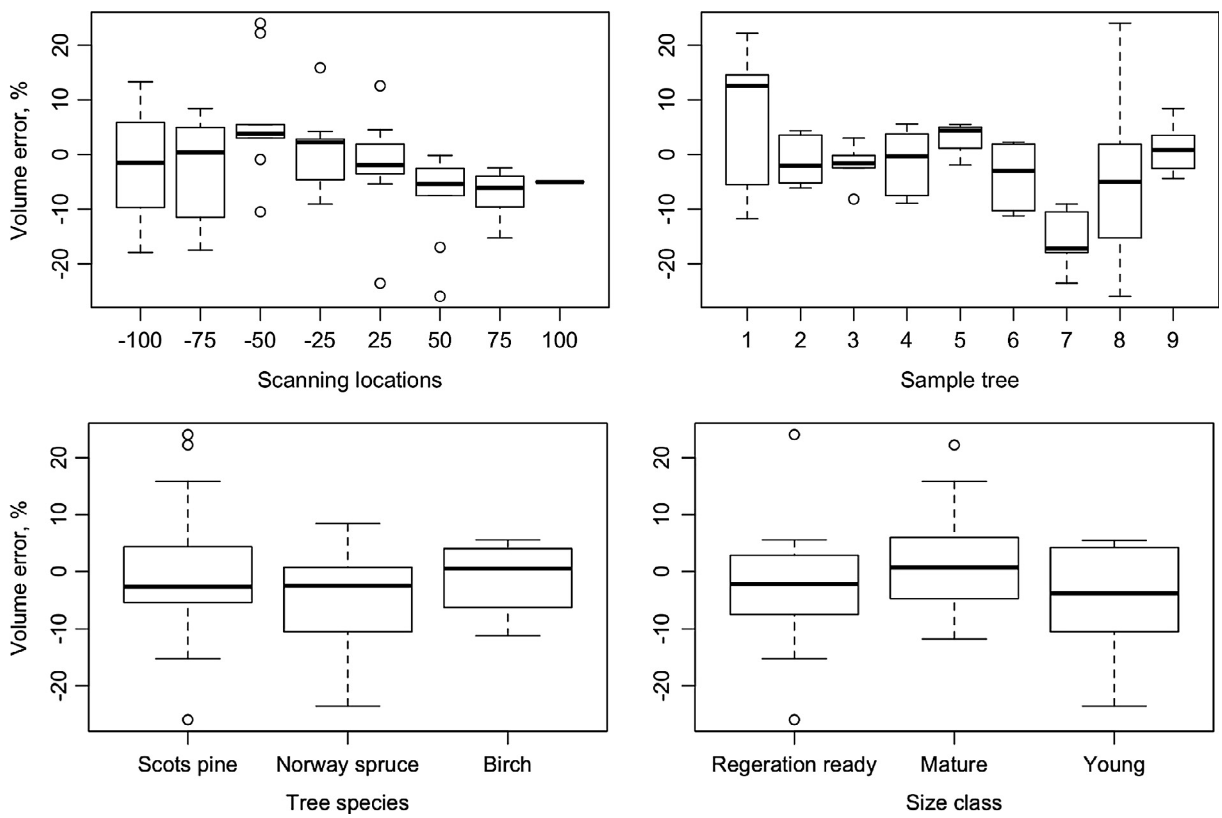

Fig. A.4. Relative volume error by scan location (upper left) and by sample tree (upper right), as well as by species (lower left) and size class (lower right).

A.5. Stem volume estimates from separately processed point clouds

Table A.5
TLS-based stem volume estimates (dm^3) for each sample tree at various scan combinations when point clouds were processed separately. Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

Tree ID	AC	AD	BC	BD
1	289.0	246.4	287.4	250.1
2	65.0	64.5	63.6	63.2
3	590.3	595.6	550.6	567.6
4	805.7	793.9	803.2	799.0
5	170.8	170.3	169.5	169.5
6	335.4	329.4	340.0	334.6
7	122.7	125.2	125.6	126.2
8	884.7	933.5	793.5	753.8
9	403.3	402.2	395.8	391.3

A.6. Stem volume estimates from combined point clouds

Table A.6
TLS-based stem volume estimates (dm^3) for each sample tree at various scan combinations when point clouds were combined. Scan locations A = −50%, B = −25%, C = +25%, D = +50%.

Tree ID	AC	AD	BC	BD
1	272.0	265.4	297.0	324.5
2	64.9	65.5	66.9	67.7
3	581.1	569.3	584.3	571.3
4	837.0	820.2	838.5	813.5
5	169.8	167.5	171.4	169.2
6	340.1	330.2	353.5	336.0
7	132.7	133.8	139.6	144.1
8	774.4	851.5	876.8	980.0
9	344.9	398.5	397.9	436.4

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